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Investigating the environmental effectiveness of Overall Thermal Transfer Value code and its implication to energy regulation development

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ABSTRACT

Building energy regulation, as part of an energy policy, is launched for governing energy-efficient building design with an ultimate goal to attain mitigation of climate change. In most of the current building energy regulations, there is no requirement for assessing the environmental effectiveness of the energy-efficient measures involved. Building professionals cannot ensure that the energy saving can offset the extra embodied energy consumed for compliance with a design regulation. This study investigates the environmental effectiveness of regulatory requirement on energy-efficient building design. A *Code of Practice for Overall Thermal Transfer Value in Buildings* implemented in Hong Kong was used as a case study. Through a survey and energy simulations, it revealed that implementation of this mandatory building design regulation in Hong Kong is successful in terms of both saving in building operating energy and recovering in embodied energy of the extra building materials used. Policy makers are advised to consider incorporating an assessment phase into the development of building energy regulation to examine the environmental effectiveness of regulatory requirement on energy-efficient building design. It is envisaged that the methodology developed in this study can be applied to other cities for evaluating the environmental effectiveness of implementing a building energy regulation.

1. Introduction

Since the energy crisis in 1970s, there has been a worldwide concern on depletion of fossil fuel which is closely linked to the socio-economic development of a society. Nowadays, the focus is shifted to the pollutants generated from consumption of fossil fuel and its adverse impact on the environment, which accelerates the rate of climate change. From the view point of energy policy, there are two major approaches for tackling this problem, namely active approach: renewable energy development; and passive approach: energy conservation. Building, as one of the major energy consuming sectors in a city, has a great potential and contribution in energy conservation through energy-efficient building design.

In a typical fully air-conditioned commercial building, the major electricity consuming systems can be ranked according to the magnitude of energy consumption as follows: (i) air-conditioning (A/C) system, (ii) electric lighting system, (iii) office equipment, and (iv) lift & escalator (EMSD, 2017). The loading of an A/C system is directly correlated with the heat gain transferring from the outdoor space through a building envelope. Around the world, there are a number of design guidelines, codes of practice or standards launched under building regulation or voluntary scheme for governing the design of energy-efficient building such as BREEAM (BRE, 2016), LEED (GBC, 2017), DGNB (DGNB, 2014), Green Mark (BCA, 2016), BEAM Plus (BEAM, 2012), ASHRAE Standard 90.1 (ASHRAE, 2016), Code of Practice for OTTV (BD, 1995), etc. One of the requirements in these design guidelines or codes of practices is to provide better thermal insulation so as to reduce the electricity consumption of A/C system in a building. For complying with the requirement of a design guideline or code of practice, building professionals can modify the design of a building wall construction by incorporating additional building components/materials such as adding thermal insulation layer; incorporating external shading device; changing glazing type; etc. to reduce heat gain transmitted into a building. There is no doubt that electricity energy can be saved through the implementation of these energy-efficient building design regulation.

1.1. Problem identified

In order to incorporate additional building components/materials for reducing heat gain into a building, there may be a substantial amount of energy consumed during production and installation of the additional building components/materials. For instance, for incorporating an overhang in a building, extra quantity of aggregate, cement and structural steel rod will be used which involve additional energy (embodied energy) consumed for raw material extraction,

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production and installation. This extra embodied energy will incur additional greenhouse gas emission as well as adverse impact on the environment.

In most of the currently adopted energy-efficient building design regulations, energy-efficient building envelope design can be assessed by either prescriptive or performance-based approach. The former, for instance, pre-sets a limit on the thermal transmittance (U-value) of an opaque wall or a maximum allowable window-to-wall ratio (WWR) for compliance with a design regulation. In performance-based approach, it provides flexibility to building professionals in designing a building with trade-off among various components of building energy consumption. Despite the fact that the design regulation can govern the design of energy-efficient building, building professionals cannot ensure that the energy saving resulted from compliance with a design regulation can offset the extra embodied energy consumed in the additional building component/material. The environmental effectiveness of the energy-saving measures in building design become doubtful. Currently, there is no requirement for assessing the environmental effectiveness of implementing an energy-efficient building design regulation.

1.2. Work done by other researchers

There are many studies on environmental assessment for buildings and construction materials by worldwide researchers with different focuses. Cavalliere et al. developed a Building Information Modelling (BIM) framework and structured building data with parameters of environmental impact into the BIM system (Cavalliere et al., 2018). Through a test case, it showed that both data reliability and consistency in information sharing could be improved by using the new BIM system. A similar research work was carried out by Panteli et al. (2018). They adopted a BIM software: Solar Analysis module of Autodesk Revit to evaluate and identify an optimal design option of building overhang from different design schemes, taking both energy and environmental performances into consideration. The findings are useful to building professionals for providing guidance and benchmark in designing bioclimatic building elements in Cyprus.

Some researchers applied technique of life cycle assessment to compare the environmental performance of different types of concrete building panels. In Malaysia, Omar et al. (2014) investigated and compared the total carbon emission (including both the direct and indirect emissions) of two different types of building panels, namely reinforced concrete panel and precast concrete panel. Their research findings revealed that application of precast concrete panel through an industrialized building system (IBS) could significantly improve the environmental efficiency of this building component. Another group of researchers, led by Biswas, also conducted a comparison work for precast concrete and ready-mix concrete under an Environmental Product Declaration of Gulf Green Mark scheme (Biswas et al., 2017). The study found that utilization of renewable solar energy and re-cycled steel in concrete production could provide substantial contribution in reducing adverse environmental impact.

Life cycle assessment was also applied to study the environmental performance of a whole building. Varun et al. (2012) evaluated the energy performance and greenhouse gas emission of an educational building in Northern India. It was found that steel and reinforced concrete cement framework occupied the major sector of greenhouse gas emission among the various types of building materials involved in the building. Moreover, the study discovered that about 60% of the total energy was consumed in the operation phase of the building for electricity supply to air-conditioning system, winter heating appliances and office equipment. In Brazil, Evangelista et al. (2018) identified and selected four typical residential buildings and assessed their environmental performance (from cradle to grave), considering eight categories of environmental impacts. The finding was similar to that from Varun. The operational phase of the residential buildings was mostly significant in terms of energy demand while the structure and foundation of the buildings contributed to the greatest impact on the environment.

For an Australian Green-Star environmental rating system, Le et al. (2018) developed a model for engineers and designers to evaluate the life-cycle energy consumption and greenhouse gas emission of commercial buildings in Australia. Four building cases had been selected to illustrate the application of the model. Their research result showed that there was an inversely relationship between the thermal resistance of a building and the building energy consumption & greenhouse gas emission. Moreover, it was reported that building materials have significant environmental impact over the life cycle of a building.

Monteiro et al. (2016) commented that the current building regulations placed too much focus on reducing building operational energy. They had carried out a life cycle assessment on two buildings – one new house and one 25-year old equivalent house in Portugal. An index, named as Embodied Energy Offset Period of Time, was found highly dependent on the operational energy of the houses. Moreover, it revealed that heavy weight concrete contributed to the major portion of embodied energy in the buildings and attention should be paid to building materials for reducing primary energy consumption and its associated environmental impact.

1.3. Research objective

The objective of this research work is to investigate and evaluate the environmental effectiveness of regulatory requirement on energy-efficient building design; and its implication to the development of building energy regulation. In this study, the quantities of resources consumed and their associated embodied energy during production and installation of various commonly adopted building components/materials constructed for energy-efficient building design will be studied through a number of building cases. Energy payback period (EPP), i.e. the length of time that a building component/material takes to offset its extra embodied energy, will be used as an index for evaluation. Subtropical Hong Kong, which is a modern finance-oriented city, was used as a case study in this research work.

In Hong Kong, the design of energy-efficient building envelope is governed by a design guideline named as *Code of Practice for Overall Thermal Transfer Value (OTTV) in Buildings* (BD, 1995) (hereafter referred as the "OTTV Code") which was enforced under a Building (Energy Efficiency) Regulation. The concept and application of Overall Thermal Transfer Value (OTTV) was firstly proposed by the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) in 1975 (ASHRAE, 1975). In the OTTV calculation, three major heat gain components are involved: (i) conduction through opaque wall (Q_{wc}), (ii) conduction through fenestration (Q_{gc}), and (iii) solar radiation through fenestration (Q_{gsol}), as expresses in Eq. (1).

$$OTTV_{wall} = \frac{Q_{wc} + Q_{gc} + Q_{gsol}}{A_{wall}} \tag{1}$$

where A_{wall} is gross area of external wall.

OTTV is a measure of average heat gain transmitted into a building through the building envelope, governing the design of a building to meet a suitable OTTV limit with an aim at reducing the electricity demand from air-conditioning system and thus the emission of greenhouse gas from power generation plant. The OTTV regulation provides an easy calculation method and a flexibility of trade-off in designing a building. OTTV is recognized as a simple and effective regulatory control on energy-efficient building design.

Since the launch of OTTV Code in Hong Kong in 1995, the OTTV control had been reviewed twice (in 2000 and 2011 respectively). In 2000, the suitable level of OTTV specified in the OTTV Code was revised from 35 W/m^2 to 30 W/m^2 (BD, 2000). After the second review in 2011, the OTTV limits were further tightened up to 24 W/m^2 (BD, 2011). This OTTV control is compulsory for both commercial and hotel

buildings in Hong Kong with focus on energy conservation in building design, without any requirement for assessing the embodied energy involved. In order to address this issue, this study was carried out to evaluate the energy payback period of various commonly adopted building components/materials to fulfill the OTTV requirement. It is envisaged that the methodology developed through this case study can be applied to other cities for evaluating the environmental effectiveness of regulatory requirement on energy-efficient building design. The details of methodology, findings and implication to energy regulation development are presented in the following sections.

2. Research methodology

2.1. Survey on existing commercial buildings with different external wall constructions in Hong Kong (1986–2017)

A survey on the design and construction of the existing fully air-conditioned commercial buildings in Hong Kong, constructed in the past 32 years (1986–2017), have been carried out. From 1986 to 2017, there are 976 commercial and 176 hotel buildings built in Hong Kong (RVD, 2018a; RVD, 2018b) from which 240 buildings have been selected for this study. Information of these 240 buildings were collected including construction details of building external walls, architectural floor plans with dimensions and orientation, number of storey, window-to-wall ratio (WWR), external shading devices, etc. This survey was conducted through a Building Records Access and Viewing On-line (BRAVO) system, launched by the Buildings Department, Hong Kong Special Administrative Region (SAR) Government (BD, 2018). The information available in this BRAVO system includes approved architectural plans, sectional views of external walls, structural calculations and related documents of completed buildings in Hong Kong.

These 32 years were divided into four periods according to the implementation and reviews of OTTV regulation in Hong Kong as shown in Table 1. There are 60 buildings selected for each period, giving a total of 240 buildings as mentioned above. The 60 buildings surveyed in each period were further divided into three different categories according to the three typical types of external wall constructions in Hong Kong, namely reinforced concrete; over-cladding and curtain walls (pls. refer to Figs. 1–3). Each wall type contains 20 building cases in each period obtained from the survey. The constitution of these 240 buildings are tabulated in Table 2.

2.2. To examine and identify the trend of change in building external wall design

For each type of the three typical external wall constructions, the major trend of building wall design that had been changed to fulfil the tightened OTTV requirement in the four periods (P_1, P_2, P_3 & P_4) were examined and analysed (based on the information collected from Section 2.1 above). For instance, as shown in Fig. 4, overhang can be widely adopted onto the top of window opening in buildings with

Table 1
Four divided periods according to the implementation and reviews of OTTV regulation in Hong Kong.

* **Period 1 (P_1)**: 1986–1995
  - Before implementation of OTTV regulation in Hong Kong
* **Period 2 (P_2)**: 1995–2000
  - OTTV regulation implemented (OTTV limit = 35 W/m^2)
* **Period 3 (P_3)**: 2000–2011
  - OTTV regulation implemented (after the 1st Review) (OTTV limit = 30 W/m^2)
* **Period 4 (P_4)**: 2011–2017
  - OTTV regulation implemented (after the 2nd review) (OTTV limit = 24 W/m^2)

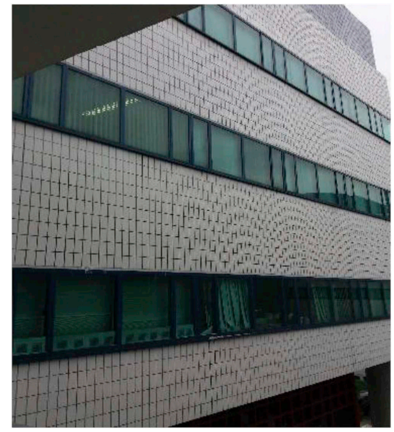


Fig. 1. Reinforced concrete wall with plaster and tile finish.

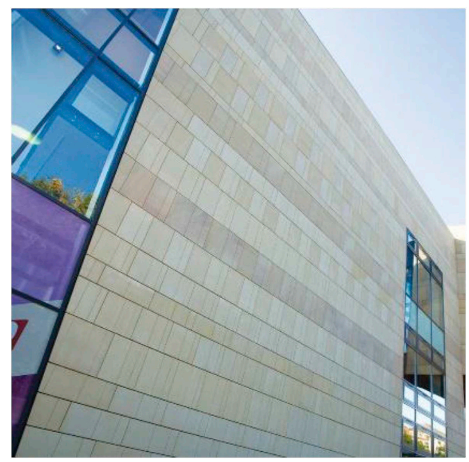


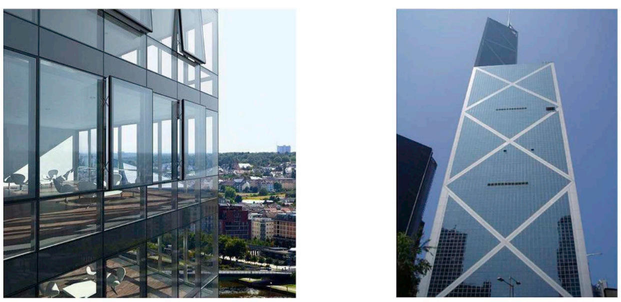
Fig. 2. Over-cladding wall with granite panel.

Fig. 3. Curtain wall construction.

Table 2
Constitution of 240 building cases.

No. of Buildings for Each Wall Type		Types of External Wall Constructions		Period of Year		Total Building Cases
20	×	* Reinforced Concrete * Over-Cladding * Curtain Wall	×	*P_1 (1986–1995) *P_2 (1995–2000) *P_3 (2000–2011) *P_4 (2011–2017)	=	240

Fig. 4. Reinforced concrete wall with overhangs.



(a) Curtain wall with clear float glass (b) Curtain wall with reflective glass

Fig. 5. Curtain wall construction with different types of glazing materials.

reinforced concrete external wall to reduce direct solar heat gain transmitted through the building envelope as well as the OTTV of a building. Fig. 5 is another example showing that a glazing material with low value of shading coefficient (SC) may be one of the energy-efficient design options for buildings constructed with curtain wall. The aim is to identify the prevailing trends of changes in building external wall design, for each type of the typical external wall constructions over the four different periods, for fulfilling the tightened OTTV limit in Hong Kong.

2.3. To establish building cases with different external wall constructions

Based on the building information obtained from the survey in Section 2.1, 20 building cases from each of the typical external wall construction types (i.e. reinforced concrete, over-cladding and curtain walls) constructed during the four divided periods (P_1, P_2, P_3, & P_4) were selected. Totally, there were 240 building cases as shown in Table 2 above.

Firstly, three base building cases (one for each type of the wall constructions) were established. A floor plan of the base case building and three sectional views of the wall constructions are depicted in Fig. 6. The OTTVs of these base building cases were calculated according to the OTTV Code and the value is equal to 35 W/m^2 which is the limit set by the Hong Kong Government in 1995 (P_2). Then, based on the results of survey on the design trends of building wall constructions, the base building cases were modified according to the prevailing design changes in each type of the wall constructions. The OTTVs of the modified building cases were set as 24 W/m^2, meeting the requirement in 2011 (P_4).

For instance, if construction of overhang and application of low-e (emissivity) glazing are identified as the prevailing trends of design in reinforced concrete wall construction, the base building case constructed with reinforced concrete external wall will be modified by incorporating these design features until the building design can meet the tightened OTTV limit of 24 W/m^2 set in 2011. With the base and modified building cases, the energy saving and the corresponding environmental effectiveness have been investigated as detailed in following two sections.

2.4. To evaluate the energy saving resulted from implementing OTTV regulation

Building energy simulation software EnergyPlus (DOE, 2013) was employed to model the base and modified building cases in this study. EnergyPlus was developed by the Department of Energy (United State), by merging two renowned simulation programs together, namely DOE-2 and BLAST. This simulation program is widely adopted by worldwide researchers to model various types of buildings, air-conditioning systems and renewable energy systems. In this research work, the annual electricity consumption of A/C system in each building case was evaluated by EnergyPlus with a Hong Kong Typical Meteorological Year (TMY) hourly weather file (Chan et al., 2006).

In each of the simulation runs, the annual electricity energy of A/C system in a base building case was compared to that of the corresponding modified building case. The difference between these two simulation results is the net annual saving in electricity energy by modifying the building design of external wall construction for fulfilling the OTTV requirement.

2.5. To evaluate the environmental effectiveness of implementing OTTV regulation

In this study, energy payback period (EPP) was used to assess the environmental effectiveness of implementing the OTTV regulation in Hong Kong. EPP is defined as the length of time an additional building component/material takes to offset its extra embodied energy, as expressed in Eq. (2). If an EPP is shorter than the lifespan of an additional component/material, the net energy saving yielded from implementing the OTTV regulation can contribute to reducing greenhouse gas emission as well as mitigation of climate change.

$$\textit{Energy Payback Period (EPP)(yrs.)} = \frac{\textit{Total Embodied Energy (MJ)}}{\textit{Annual Energy Saving}\left(^{MJ}/_{yr}\right)} \tag{2}$$

In each modified building case, the quantity of each additional material was calculated first. Then the embodied energy was determined by multiplying the quantity (mass) of each material by the corresponding embodied energy intensity (MJ/kg). By summing up the embodied energy of all the additional materials in the modified building case, the total embodied energy can be determined. Finally, the EPP of a modified building case was calculated by dividing the total embodied energy by the annual energy saving of the modified building case, as expressed in Eq. (2).

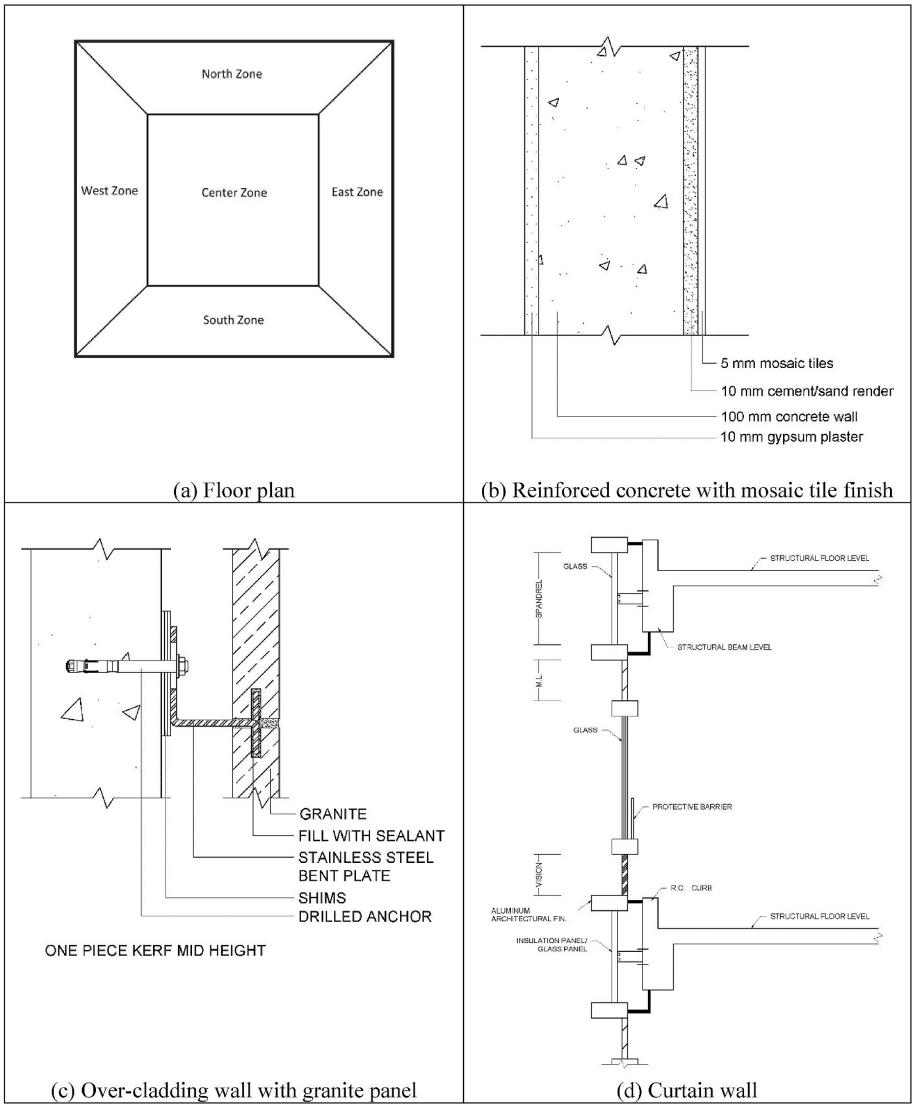


Fig. 6. Floor plan of base building case and sectional views of three wall constructions.

3. Results

3.1. Survey on trend of building wall design

Through a survey on the design of the existing fully air-conditioned commercial buildings which were constructed in the past 32 years (1986–2017) in Hong Kong, the prevailing trends of changes in building external wall design for each type of the typical external wall constructions over four different periods (P_1 to P_4) are tabulated in Table 3. The trend of change in building wall design are expressed in terms of five design parameters, namely window-to-wall ratio (WWR), shading coefficient of glazing material (SC), thermal transmittance of opaque wall (U-value), thermal absorptivity of opaque wall (α) and depth of overhang (OH). The data of these design parameters listed in Table 3 are average values in each of the four periods.

As seen from Table 3 (a), there is a tendency in reducing WWR for concrete wall construction from 56.91% in period P_1 to 39.49% in period P_4 for fulfilling the tightened up OTTV requirement in Hong Kong. As Hong Kong is located in the subtropical region with plenty of solar radiation in her long and hot summer season, a smaller building WWR can yield substantial reduction in solar heat gain as well as OTTV of a building. Moreover, it was found that the average depth of overhang (OH) has been increased from 0.317 m in P_1 to 1.02 m in P_4,

Table 3
Summary on design trends for three different wall construction types over four different periods.

	P_1	P_2	P_3	P_4
(a) Reinforced Concrete Wall Construction				
WWR	56.91%	51.46%	43.78%	39.49%
SC	0.529	0.504	0.503	0.582
U-value	1.863	1.809	1.746	1.870
α	0.635	0.606	0.587	0.61
OH[a]	0.317	0.7	0.91	1.02
(b) Over-Cladding Wall Construction				
WWR	74.64%	63.64%	64.04%	51.80%
SC	0.475	0.471	0.478	0.407
U-value	0.797	0.586	0.419	0.465
α	0.404	0.359	0.388	0.42
OH[a]	0	0.65	0.5	0.58
(c) Curtain Wall Construction				
WWR	50.79%	65.25%	67.87%	71.04%
SC	0.373	0.295	0.273	0.22
U-value	0.623	0.402	0.279	0.358
α	0.607	0.665	0.691	0.73
OH[a]	0	0	0.086	0

[a] OH: Depth of overhang (m).

which is effective to shade a window from direct solar radiation. On the contrary, the average values of SC, U-value and α are quite stable over the four periods.

Table 3 (b) lists the trend of design for the second type of wall construction – over-cladding. Both the SC and α show insignificant fluctuation in their average values over the four periods. On the other hand, it is observed that there is a trend of decrease in the WWR and U-value for reducing heat transmission through building envelope for fulfilling the tightened OTTV requirement. Moreover, overhang was adopted in some buildings for reducing transmission of direct solar radiation through glazing area. The average depth of overhang ranges from 0.5 m to 0.65 m.

For curtain wall construction, Table 3 (c) shows that the average values of WWR were gradually increased from 50.79% (P_1) to 71.04% (P_4) over the surveyed periods. In Hong Kong, curtain wall construction is primarily adopted in high-class commercial buildings in which large WWR for view enjoyment is generally requested by the building developers and tenants. In order to fulfill the tightened up OTTV requirement, it can be indicated by the surveyed data in Table 3 (c) that glazing materials of lower SC (decreased from 0.373 in P_1 to 0.22 in P_4) were used. Moreover, the average U-value of spandrel panel was decreased (from 0.623 W/m^{2}K to 0.358 W/m^{2}K) in order to offset the increased solar heat gain which was incurred by the larger WWR in building design. The values of α is quite stable and overhang is not commonly adopted in buildings with curtain wall construction in Hong Kong.

3.2. Building cases established

Based on the survey on building design trend, base building cases and modified building cases have been established for the three wall construction types. In Table 4 (a), a base case with WWR of 61.5% was established for concrete wall construction. The values of SC, U-value and α are 0.35, 2.32 W/m^{2}K and 0.58 respectively. According to the OTTV Code in Hong Kong, the OTTV of this base building case was calculated as 35 W/m^2 which meets the OTTV limit launched in P_2 (1995–2000). Then the base case was modified by reducing the WWR from 61.5% to 40% (while the other parameters remain unchanged) to establish a modified building case (MC1) with an OTTV of 24 W/m^2, which fulfills the OTTV requirement set in P_4 (2011–2017). The second modified building case (MC2) was incorporated with an overhang (OPF = 0.55) while the WWR was kept as that of the base case. OPF (Overhang Project Factor) is defined as a ratio of overhang depth to the vertical distance from the bottom of the overhang to the windowsill. The OTTV of this modified building case MC2 is also equal to 24 W/m^2.

The establishment of the base and modified building cases (MC1 and MC2) for over-cladding wall construction follows a similar approach and the data are listed in Table 4 (b). The value of WWR was set as 39.5% for MC1 while the OPF of the overhang in MC2 was 0.5. In addition, as found from the survey, there is a trend of reducing U-value for the over-cladding wall construction. Based on this finding, another modified building case MC3 with a reduced U-value (from 1.732 W/m^{2}K (base case) to 0.465 W/m^{2}K) was established. Compared to solar heat gain through window glazing, the heat energy transferred through opaque wall is relatively insignificant. As a result, the OTTV in MC3 is merely reduced from 35 W/m^2 (base case) to 34.2 W/m^2 even though there is a change in the U-value of the over-cladding wall construction.

To set up a base case (with OTTV of 35 W/m^2) for the curtain wall construction, a WWR of 50% with SC of 0.43 were used. The magnitudes of the U-value and α are 0.623 W/m^{2}K and 0.607 respectively, as indicated in Table 4 (c). By making reference to the surveyed data from Table 3(c), the WWR and SC of the base case were then changed to 70% and 0.22 respectively for establishing a modified case (MC1) with an OTTV of 24 W/m^2.

Table 4
Building cases established for three different wall construction types.

(a) Concrete Wall Construction

	Base Case	Modified Case 1 (MC1)	Modified Case 2 (MC2)
OTTV	35 W/m^2	24 W/m^2	24 W/m^2
WWR	61.5%	**40%**	61.5%
OH (OPF)[a]	0	0	**0.55**
SC		0.35	
U-value		2.32	
α		0.58	

(b) Over-Cladding Wall Construction

	Base Case	Modified Case 1 (MC1)	Modified Case 2 (MC2)	Modified Case 3 (MC3)
OTTV	35 W/m^2	24 W/m^2	24 W/m^2	34.2 W/m^2
WWR	60%	**39.5%**	60%	60%
OH (OPF)	0	0	**0.5**	0
SC			0.36	
U-value	1.732	1.732	1.732	**0.465**
α	0.6			

(c) Curtain Wall Construction

	Base Case	Modified Case 1 (MC1)
OTTV	35 W/m^2	24 W/m^2
WWR	50%	**70%**
OH (OPF)		0
SC	0.43	**0.22**
U-value		0.623
α		0.607

[a] OPF = Overhang Project Factor.

3.3. Simulation results

The building cases established in Section 3.2 above were modelled by using a building energy simulation program EnergyPlus. Simulation runs were conducted with a Hong Kong Typical Meteorological Year (TMY) hourly weather file and the results, in terms of annual energy consumption (MJ/yr.), were plotted in Fig. 7 for illustration.

The first set of bar chart shows the annual energy consumption for the base and modified building cases of concrete wall construction. It indicated that, with the modified building cases of reduced WWR (MC1) and incorporation of overhang (MC2), the percentages of annual saving are 6.23% and 8.25% respectively.

The simulation results of over-cladding wall construction show a similar trend. The modified case (MC1) gives a percentage of annual energy saving of 7.4% and the second modified case (MC2) offers a result of 8.31%. A saving of 2.03% comes from the modified case (MC3) in which a reduced U-value was used in this building case. The percentage of saving in this modified case MC3 is in line with the reduction of OTTV from 35 W/m^2 (base case) to 34.2 W/m^2 (MC3) which gives a reduction percentage of 2.29%.

The last set of bar chart presents the annual energy consumption of the base and modified building case with curtain wall construction. When compared to the base building case, an annual energy saving of 6.97% was found.

3.4. Environmental assessment

In this study, energy payback period (EPP) was adopted to evaluate the environmental effectiveness of implementing the OTTV control on energy-efficient building design. EPP was calculated as the ratio of embodied energy to the net annual electricity saving. It can be interpreted as the length of time an additional building component/material takes to offset its extra embodied energy consumed for fulfilling the OTTV requirement.

Table 5 (a) lists the data and calculation result of the modified

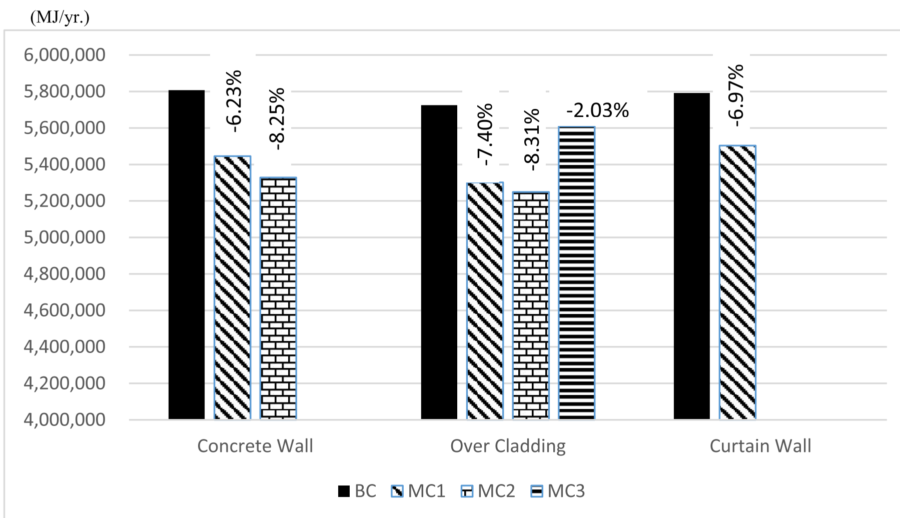


Fig. 7. Simulation result on annual energy consumption for various building cases.

building case (MC1) with reduced WWR for concrete wall construction. In Hong Kong, a conventional concrete wall construction typically consists of a 5 mm mosaic tile (outer layer), 10 mm cement render, 100 mm heavy weight concrete with structural steel rod inside, and 10 mm gypsum plaster (inner layer). The data of embodied energy intensity (MJ/kg) and the quantity (kg) of each type of building material consumed for reducing the WWR are shown in columns (a) and (b) of Table 5 (a), respectively. In Hong Kong, a Life Cycle Energy Analysis (LCEA) assessment tool for analysis of building construction has been launched by the Hong Kong SAR Government which provides data of embodied energy intensity for the present study (EMSD, 2005). The embodied energy of each type of building material was calculated by multiplying the data in column (a) by the data in column (b), giving the result in column (c).

It is noted from column (b) that the mass of glass is negative (−74,762 kg). As the WWR of this modified building case is reduced, extra building materials are consumed for the increased area of concrete wall while the area as well as the material of the glazing material will be reduced, resulting in a negative mass of glass material in the calculation of total embodied energy for this modified building case. The total embodied energy is the sum of the products of (a) and (b) which equals to 1,433,579 MJ. The final step is to divide this total embodied energy by the annual energy saving of 361,882 MJ (which was determined by building energy simulation in the previous section), giving a value of EPP: 3.96 years, This is the length of time that this modified building case with reduced WWR takes to offset its extra embodied energy incurred, which is used as an index for this evaluation.

The second modified building case of concrete wall construction (MC2) was incorporated with overhang in which only concrete and structural steel rods are involved, as shown Table 5 (b). Since the WWR in this modified building case remains the same as that in the base case, there is no deduction of glass material in the calculation of total embodied energy. The EPP for this modified building case is 6.06 years.

The EPPs of the modified building cases of over-cladding wall construction (MC1) and (MC2) were determined by using the similar steps and the results are 4.77 and 5.41 years respectively, as listed in Table 5 (c) and (d).

As described in Section 3.1, the trend of design change in curtain wall construction is increased WWR with reduced SC. For a building case with reduced WWR, the area of glazing is reduced while the area of opaque spandrel wall is accordingly increased. Table 5 (e) shows that the amount of extra embodied energy for glass material (1,056,150 MJ) is less than the reduced embodied energy of spandrel wall (including mineral wool insulation (−146,101 MJ) and steel cover panel (−1,391,887 MJ)), resulting in a negative total embodied energy (−481,838 MJ) for this modified building case. It can be interpreted as double benefits, i.e. there are savings in both the total embodied energy and operating energy through this modification of curtain wall construction for fulfilling the OTTV requirement.

However, it cannot be concluded that curtain wall construction can supersede the other two types of typical wall constructions in Hong Kong. It is because there are various factors to be considered in selecting an appropriate type of wall construction for a building, such as construction cost, glare problem, acoustic insulation, privacy, security, etc. In Hong Kong, curtain wall is primarily adopted in high-class commercial buildings. The unit construction cost for curtain wall in Hong Kong ranges from HK\$6600/m^2 to HK\$8500/m^2 (1 USD = HK \$7.8) which is expensive when compared to that of concrete wall construction with mosaic tile finish (HK\$1300/m^2 to HK\$1400/m^2) (ASD, 2018). On the other hand, concrete wall construction can offer a better performance in terms of glare control and sound insulation. The building developer and designer can select an appropriate type of wall construction according to their requirements on a building project.

Nonetheless, the EPPs of all the modified building cases in this study are within an acceptable period of time (i.e. less than 7 years). Through this environmental assessment, it reveals that the implementation of the mandatory energy-efficient building design regulation (OTTV Code) in Hong Kong is successful in terms of both saving in building operating energy and recovering in embodied energy of the extra building materials used.

4. Conclusion and policy implication

The objective of this study is to evaluate the environmental effectiveness of implementing energy-efficient building design regulation. Hong Kong, as a modern city located in subtropical region, was used as a case study. A survey on 240 existing commercial buildings in Hong Kong had been conducted to identify the prevailing trend of change in building wall design. Based on the data and information acquired from the survey, a number building cases were established to evaluate the embodied energy as well as the energy payback periods of additional building component/materials consumed for fulfilling a building energy regulation – *Code of Practice for Overall Thermal Transfer Value (OTTV) in Buildings* in Hong Kong.

The research findings reveal that the energy payback periods for all the building cases of three typical wall construction types in Hong Kong, namely concrete wall, over-cladding wall and curtain wall, are

Table 5
Calculation of energy payback period (EPP) for various modified building cases.

Material	(a) Embodied Energy Intensity (MJ/kg)	(b) Mass (kg)	(c) = (a) x (b) Embodied Energy (MJ)
(a) Concrete Wall Construction: Modified Case 1 (MC1)			
Mosaic tile	12	31,150	373,800
Cement render	1.43	46,351	66,282
Concrete	1.9	598,080	1,136,352
Structural steel rod	38.016	23,429	890,679
Gypsum plaster	5.56	27,910	155,182
Glass	15.9	−74,762	−1,188,716
		Total Embodied Energy =	1,433,579
		Annual Saving =	361,882
		EPP =	3.96 (yrs.)
(b) Concrete Wall Construction: Modified Case 2 (MC2)			
Concrete	1.9	856,320	1,627,008
Structural steel rod	38.016	33,545	1,275,258
		Total Embodied Energy =	2,902,266
		Annual Saving =	478,977
		EPP =	6.06 (yrs.)
(c) Over-Cladding Wall Construction: Modified Case 1 (MC1)			
Granite	5.9	181,605	1,071,467
Concrete	1.9	570,269	1,083,512
Structural steel rod	38.016	22,340	849,263
Gypsum plaster	5.56	26,613	147,966
Glass	15.9	−71,286	−1,133,441
		Total Embodied Energy =	2,018,766
		Annual Saving =	423,495
		EPP =	4.77 (yrs.)
(d) Over Cladding Wall Construction: Modified Case 2 (MC2)			
Concrete	1.9	759,556	1,443,156
Structural steel rod	38.016	29,755	1,131,154
		Total Embodied Energy =	2,574,310
		Annual Saving =	475,776
		EPP =	5.41 (yrs.)
(e) Curtain Wall Construction: Modified Case 1 (MC1)			
Glass	15.9	70,410	1,056,150
Mineral wool insulation	16.6	−8801	−146,101
Steel sheet	38.016	−36,613	−1,391,887
		Total Embodied Energy =	−481,838
		Annual Saving =	248,372
		EPP =	0 (yrs.)

within a reasonable period of time (less than 7 years). Moreover, it was found that a modified building case for curtain wall construction with increased window-to-wall ratio and lower shading coefficient could offer double benefits: (i) reduced solar heat gain and electricity consumption in the building case; and (ii) reduction in net embodied energy consumed in the building materials of the curtain wall construction. The result of this study indicated that the implementation of an energy-efficient building design regulation (OTTV Code) in Hong Kong can achieve a good environmental effectiveness, i.e. the energy saving from building operation can offset, and is even much greater than the embodied energy consumed in the extra building materials for meeting the building design regulation.

Building energy regulation, as part of an energy policy, is launched for governing energy-efficient building design with an ultimate goal to attain mitigation of climate change. The OTTV regulation assessed in this research work is also implemented in other countries including Singapore, Philippines, Thailand, Malaysia, Indonesia, Jamaica and Ivory Coast for energy-efficient building design. In addition, there are other commonly adopted building design guidelines under various energy regulations or voluntary schemes such as BREEAM, LEED, DGNB, Green Mark, BEAM Plus and ASHRAE Standard 90.1.

For developing a building energy regulation, it generally starts on a voluntary basis in a format of energy-efficient building design guideline. Incentive such as tax reduction, GFA (gross floor area) concession, certificate of merit, etc. may be offered by the government to promote the newly launched regulation. Feedback and suggestions will be collected from stakeholders. After a period of trial run, there may be revision on the building energy regulation. In most of the cases, the requirement of the regulation will be tightened up for achieving a higher energy efficiency and the building energy regulation will eventually become mandatory for all new building designs. Policy makers are advised to consider incorporating an assessment phase into the development of building energy regulation to examine the environmental effectiveness of regulatory requirement on energy-efficient building design. It is envisaged that the methodology developed through the case study in this research work can be applied to other cities for evaluating the environmental effectiveness of implementing a building energy regulation.

In addition to energy-efficient building envelope design, building energy regulation also has requirement on energy efficiency of heating, ventilating and air-conditioning (HVAC) system. In Hong Kong, the government has formulated a Code of Practice for Energy Efficiency of Building Services Installation" (hereinafter referred as the "Building Energy Code) (EMSD, 2018). This Building Energy Code sets out technical guidance and details in respect of the minimum energy efficiency requirements for governing the design of energy-efficient building services installations, including the HVAC system. For instance, there are prescribed requirements on minimum coefficient of performance (COP) of various types of chillers; minimum thickness of thermal insulation on air ductwork and water pipework; limit on motor power (W/litre per second) for air fan and water pump; efficient control system; etc.

Currently, the embodied energy of energy-saving measures in HVAC system is not taken into consideration under the Building Energy Code. Financial return on an additional energy-saving device/system is the major concern of most building owners. The actual benefit in terms of environmental conservation yielded from energy efficiency requirement may be questionable. Therefore, assessing the environmental effectiveness of regulatory requirement on energy-efficient design of HVAC and other building services systems will be a deserving future research work and potential policy development.

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